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Abstract. A computer model of a simplified pressurized nuclear power plant is developed with aim at studies concerning process control, diagnosis and decision making.

The model includes the traditional PWR plant components, primary circuit with reactor, pressurizer and steam generator, steam circuit with steam line, turbine and condenser, interconnected with pumps, valves and controllers. The model can be used for calculation of transients for both normal operation and incidents such as turbine trip, loss of feedwater, run down of pumps or various valve failures.

The computer model is not directed to any specific existing plant. For convenience and alleviation in implementation the physical description of many components are simplified to an extent where the qualitative behavior of the system is not violated. For computer memory economy a variety of thermodynamical functions for water and steam have been approximated with analytical expressions base on table values.

The model is implemented in the C language and has been run on both the IBM PC and the SUN workstation.

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Contents

1 Introduction

This report describes a computer simulation of a simplified pressurized nuclear power plant model directed towards process control, diagnosis and decision making.

The physical power plant model is intended to be integrated into a real time data base management system, where the physical process simulation should be monitored concurrently with a number of tasks such as operator input, information display, limit checking activity, data recording and malfunction handling.

The model is an enlargement of a previous model used for studies of operator activities (*Højberg*,1982) as some changes have been performed concerning functional structure and complexity. New components have been added to the model and the numerical strategies used for solving the state variable differential equations have been modified.

2 System description

The power plant model is depicted in figure 1. It includes all basic PWR components as lumped elements interconnected by ideal frictionless pipes. The PWR power plant is a 856 MW single loop heat transport system with a vertical U-tube natural recirculation type steam generator and a single primary pump. A pressurizer is located on the hot reactor leg and a volume control system is connected to the cold leg. The reactor is simulated as a very simplified one-dimensional nuclear system without reactivity feedback mechanisms, coolant boron concentration systems or possibility of steam production and void formation. The power generated is controlled by a single control rod regulated by a simple rod drive mechanism.

The single steam line connects the steam generator with a turbogenerator system consisting of a single high pressure turbine driving a 30 KV electric generator. The feedwater system consists of a condenser connected to the steam generator via a single pump. A single bypass valve is available for steam dump directly to the condenser and safety valves are present for both the pressurizer and steam line system.

No attempt is made to include moisture separation or preheater systems. Moreover the model includes lubrication systems with filter components for the reactor coolant pump and the feedwater pump.

Six main control systems are incorporated in the model - control of reactor power by regulation of control rod position, control of primary pressure by regulation of spray valve cooling flow or pressurizer heating, control of water level in the pressurizer by regulation of letdown and charging coolant flows, control of steam line pressure by regulation of reactor power demand, control of water level in the steam generator by regulation of feedwater pump flow and control of generator voltage by regulation of turbine valve position.

The model can be used for calculating transients for both normal and abnormal occurences with only few limitations. In the primary coolant system two-phase flow is not allowed and pressurizer and steam generator volumes may not be emptied or overfilled. Pressures should be within the range from 0.01 bar to 200 bar and temperatures in the range from 10 to 350 Celcius degree. Under these wide conditions severe transients may be simulated such as loss of cooling accidents, loss of load, loss of feedwater or failure in various valves, pumps and controllers.

All pumps, control valves and controllers in the model operate in either auto/manual or failed mode, and all pumps, valves and controller components are thus prepared for malfunction accidents.

2.1 Nomenclature and component list

The plant model components are identified a single numbers with reference to figure 1 and listed in the following table

Table 1. Plant model components

reactor (1)	steam generator tube side (2)
steam generator shell side (3)	condenser tube side (4)
condenser shell side (5)	turbine/generator (6)
pressurizer (7)	volume control tank (8)
cooling water reservoir (9)	steam line safety valve (10)
turbine valve (11)	steam line bypass valve (12)
pressurizer spray flow valve (13)	coolant let down valve (14)
pressurizer safety valve (15)	reactor cooling system oil filter (17)
feedwater system pump oil filter (18)	cooling water system pump filter (19)
reactor coolant pump (20)	feedwater pump (21)
cooling water pump (22)	reactor coolant charging pump (23)
reactor cooling system oil pump (24)	feedwater system oil pump (25)
steam generator level controller (30)	steam generator pressure controller (31)
generator voltage controller (32)	pressurizer level controller (33)
pressurizer pressure controller (34)	

Physical process variables used in the power plant simulation are listed in appendix A and grouped in state variables, parameters and constants. All process variables are identified by short symbols indexed by a number refering to the defining physical component (figure 1). Process variable symbols used in this report appears in the same font as used in table 1.

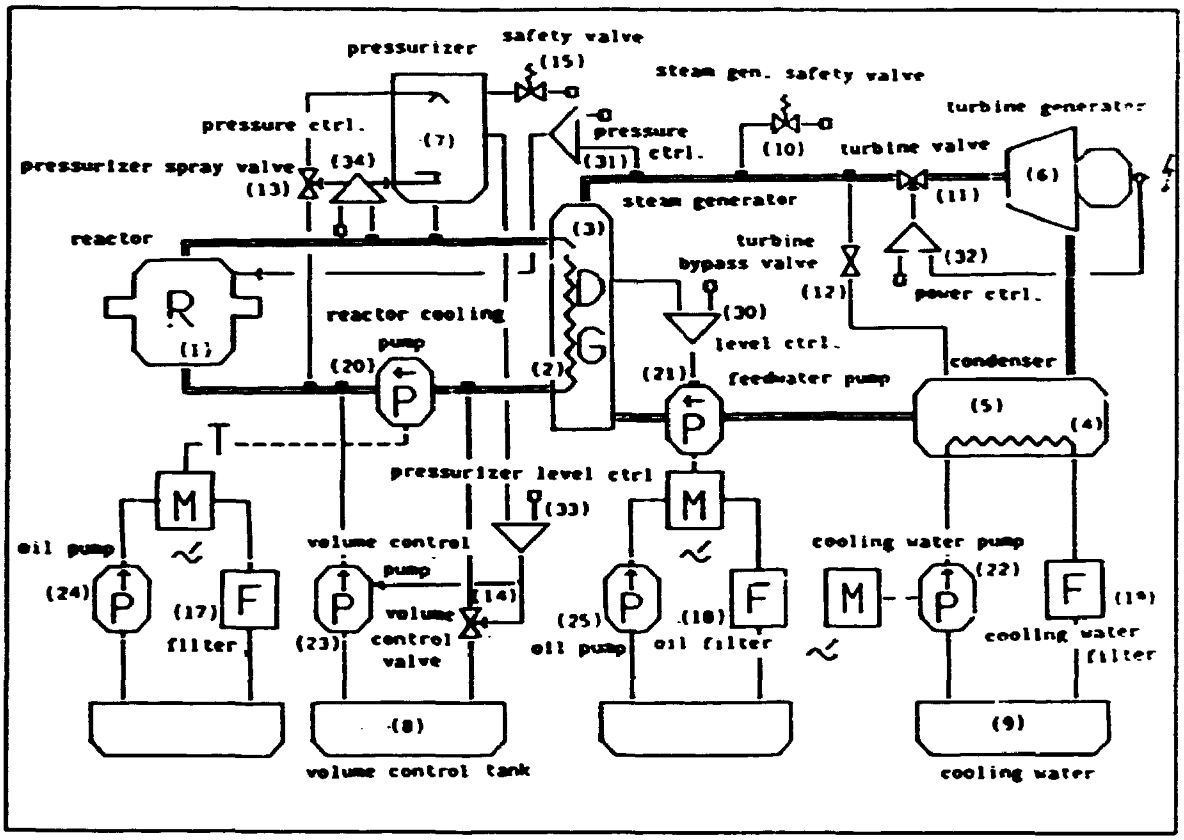

Figure 1. The PWR Power Plant

2.2 Thermodynamical functions

In the computer simulation the accurate calculation of a variety of thermodynamical functions for water and steam plays a significant role for the reliability of the model.

The thermodynamical functions used in the plant model are summarized in Table 2.
The argument P denotes pressure in bar, T temperature in Celcius degree and u specific energy MJ/Kg.

Table 2 - Thermodynamical functions

$\rho_w(T)$	density of water (unsaturated)	Kg/m^3
$\rho_f(P)$	density of saturated water	Kg/m^3
$\rho_g(P)$	density of saturated steam	Kg/m^3
$h_w(T)$	enthalpy of water (unsaturated)	MJ/Kg
$h_f(T)$	enthalpy of saturated water	MJ/Kg
$h_g(P)$	enthalpy of saturated steam	MJ/Kg
$s_f(P)$	entropy of saturated water	MJ/Kg
$s_g(P)$	entropy of saturated steam	MJ/Kg
$T_s(P)$	temperature of saturated steam	°C
$T_w(u)$	temperature of water (unsaturated)	°C
$\frac{d}{dt}\rho_w(T)$	water density gradient	$Kg/m^3/°C$

Table values for all steam and water functions, except density of water, are found in (*Wasserdampftafeln*,1963) and have to be approximated by analytical expressions due to computer memory limitation. Common to all these strong non-linear functions is that they all refuse polynomial approximation of modest order through the relative wide range needed for pressure (from 0.01 bar to about 200 bar) and for temperature (from 10 to about 350 Celcius degree), if an accuracy better than 1 per cent should be achieved. The approximation method used is to split the functions over appropriate subintervals and fit the functions piece by piece by either polynomials or rational functions of modest degree.

The approximations from table values were calculated by a standard library algoritm (*Wiese*,1969), which performs the approximations using the Chebyshev norm for minimizing the maximal relative derivation from the exact table values. The approximation results are tabulated in appendix E.

The enthalpy function $h_w(T)$ and the temperature function $T_w(u)$ are applied for unsaturated primary coolant water, and hence the functions should be pressure dependent. However, two-argument analytical approximations is avoided, and as the pressure dependency is of minor importance compared to temperature dependency, a compromise is performed approximating the functions for fixed high pressure (150 bar).

The density function $\rho_w(T)$ is calculated by use of an expression derived from a formula quoted in (*Keeman & Keyes*,1948). This formula originally contains both pressure and temperature arguments, but the pressure dependency is omitted due to its minor significance.

The approximation used in the model is

$$\rho_w(T) = \frac{1000.0}{3.086 - 0.8990(374.1 - T)^{0.14717}} \quad Kg/m^3$$

3 System modeling

The thermal dynamic models for the plant components are lumped parameter descriptions based on basic physical equations, and the plant model is described by mass and energy conservation laws. The plant model is not directed to any specific existing plant, and hence the physical description of all components are simplified to an extent where the qualitative behavior of the system is not violated. In general this is done by linearizations which makes computing faster and simplifies involved implicit algebraic structures and their analytical solution. Verifications by comparison of transients from simulators simulating similiar models of the PWR type has not been made as many of the data used are only provisional. Available data is adapted from a Westinghouse PWR power plant.

The mathematical details of the plant component description are outlined in (*Lind*,1982). In the following sections the actual mathematical equations used are quoted with figures, and parantesized numbers refer to these equations.

The model is implemented in the C language and has been run on both IBM PC and the SUN workstation.

3.1 Main units representation

3.1.1 Reactor model

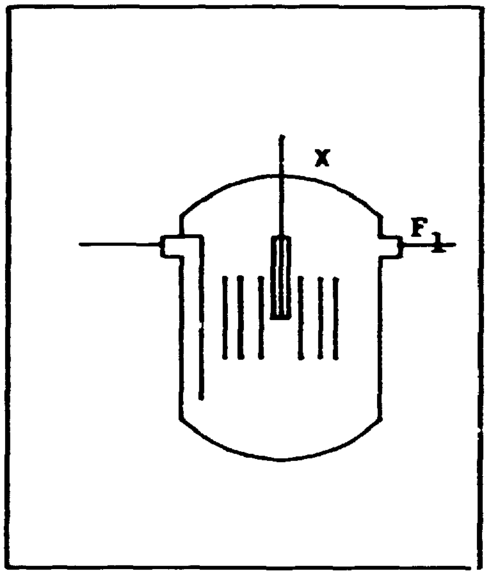

Figure 2. Reactor model

reactor effect equation

$$\frac{d}{dt}Q_1 = C_1(x_1 - x_r)Q_1 \tag{2.1}$$

energy balance equation

$$\frac{d}{dt}U_{11} = F_1(u_2 - u_1) + Q_1 \tag{2.2}$$

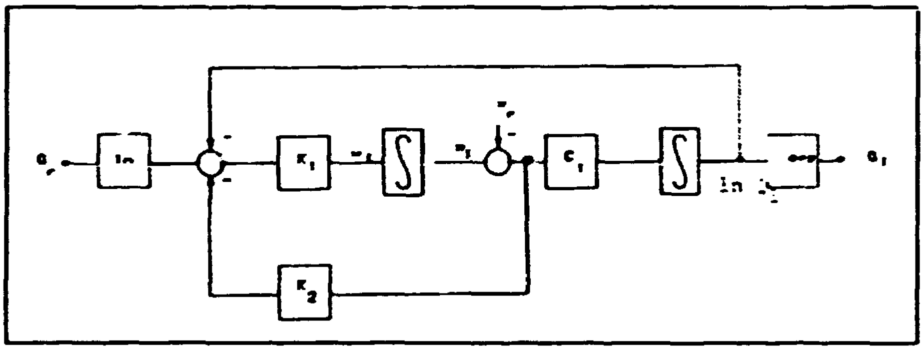

Figure 3. Reactor rod bank dynamics

reactor rod dynamics

$$w_1 = \frac{d}{dt}x_1 = K_1\left(\ln\frac{Q_r}{Q_1} - K_2(x_1 - x_r)\right) \tag{3.1}$$

The reactor equations used are quoted with figure 2. Only the energy balance equation (2.2) is used for the reactor vessel water volume, assuming constant water mass. An estimation of the reactor reactivity constant C_1 from more accurate kinetic equations is performed in appendix A. The reactor effect Q_1 is determined only by the control rod position x_1 which is governed by a control mechanism depicted by figure 3. In this drive mechanism (3.1) the rod velocity w_1 depends on actual rod position x_1, the ratio of reactor effect demand Q_r and actual effect Q_1. Choosing appropriate values for the controlling constants K_1 and K_2 intended values for the control loop frequency and damping ratio may be achieved given suitable smooth bank movement (cf. 3.2.3).

Process variables submitted to auto/manual control and malfunction handling are control rod reference x_r and velocity w_1 (cf. 3.4.5). Also an input constant should be specified to the model limitating the speed of the rod bank to a fixed maximal rate.

3.1.2 Pump model

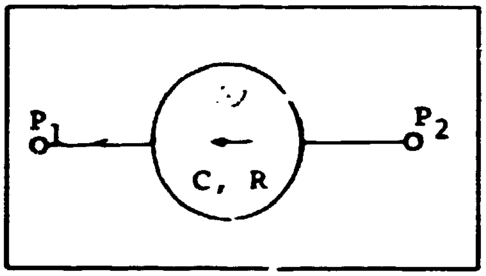

Figure 4. Pump model

pump characteristic

$$\Delta P = C\omega - RF, \quad \Delta P = P_1 - P_2 \qquad (4.1)$$

The model, shown in figure 3, simulates four centrifugal pumps: primary cooling (20), feed water (21), cooling water (22) and volume control pump (23). Although only the feed water and the volume control pump are treated as pumps driven by variable speed motors, all pump/motor systems are implemented by the same prototype model. This contributes to convenience in programming and consistency in treatment of pump parameters. Further it is only the qualitative behavior of the pump system which have interest to the power plant model, and hence the pump characteristic is aproximated by a simple linear expression (3.1) connecting the pressure head DP shaft angular velocity ω and mass flow rate F. The pump constant C and the pump friction factor R are estimated from mass flow rate and pump velocity under steady state conditions and not from real pump data.

The pump model also includes two real-valued process parameters, an error parameter for malfunction capabilities, which simulates accidents such as loss of power and failed pump speed, and an auto/manual flag for manual operation (cf. 3.4.4).

3.1.3 Control valve model

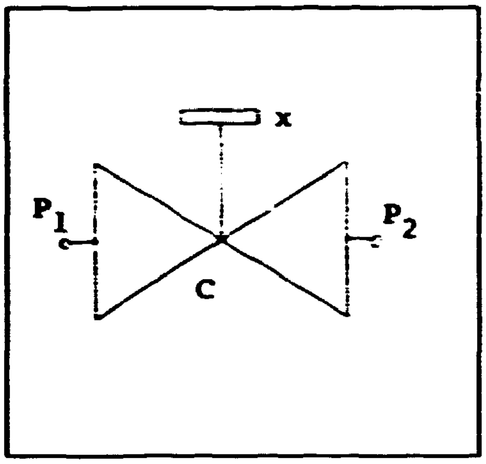

Figure 5. Control valve model

valve characteristic

$$F = xC\Delta P, \quad \Delta P = P_1 - P_2 \qquad (5.1)$$
$$0 \le x \le 1$$

The operational equation is linearized in analogy to the pump model, as exact quantitative valve behavior is of minor interest for the simulation purpose and further this is convenient in dealing with the turbine equations (cf. 3.1.8). The model also includes two real-valued process parameters, an error parameter and an auto/manual control parameter. These parameters transfer the error/control input values to the valve position parameter (cf 3.4.1).

3.1.4 Safety Valve model

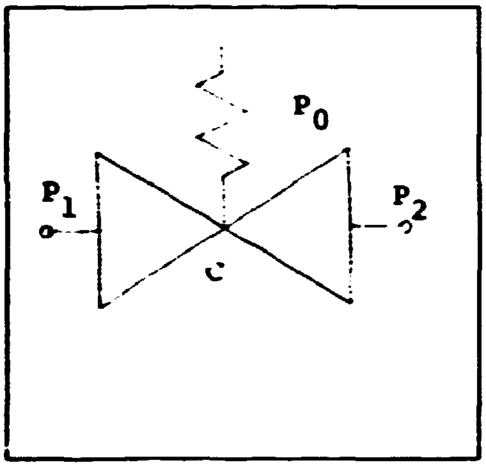

Figure 6. Safety valve model

valve characteristic

$$F = xC\Delta P, \quad \Delta P = P_1 - P_2$$
$$x = \begin{cases} 0 & \Delta P < P_0 \\ 1 & \Delta P \ge P_0 \end{cases} \qquad (6.1)$$

This valve model operates with a linear characteristic of the same form as the control valve, but the valve position is treated as an internal parameter put to zero under normal conditions, but raised to unity when the pressure differential exceeds the pressure setpoint, or it may be set to an intermediate value by an error parameter for simulation of a stuck valve (cf. 3.4.2).

3.1.5 Pressurizer model

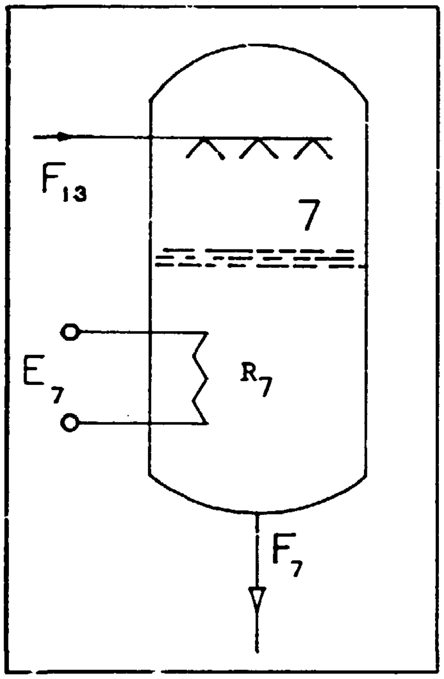

Figure 7. Pressurizer model

dynamic equations

$$\frac{d}{dt}U_7 = F_{13}u_2 - F_7u_7 + Q_7 \tag{7.1}$$

$$\frac{d}{dt}M_7 = F_{13} - F_7 \tag{7.2}$$

where

$$Q_7 = \frac{E_7^2}{R_7}$$

$$u_2 = \frac{U_2}{M_2}$$

$$u_7 = \begin{cases} h_f(P_7) & \text{for } F_7 \geq 0 \\ u_1 & \text{for } F_7 < 0 \end{cases}$$

two-phase equations

$$\alpha_7 = \frac{V_{f7}}{V_7}$$

$$U_7 = V_7(\alpha_7\rho_f(P_7)h_f(P_7) + (1 - \alpha_7)\rho_g(P_7)h_g(P_7)) \tag{7.3}$$

$$M_7 = V_7(\alpha_7\rho_f(P_7) + (1 - \alpha_7)\rho_g(P_7)) \tag{7.4}$$

$$T_7 = T_s(P_7) \tag{7.5}$$

The pressurizer is implemented with a single cooling spray armature and a heater element for pressure control (figure 4). The pressurizer spray flow F_{13} are taken from the cold leg of the primary loop and controlled by the spray flow control valve. The heater is controlled by a variable voltage E_7 The pressurizer is normally filled with nearly equal volumes of saturated water and steam, and the applied two-phase equations (7.3-4) are solved for pressure and relative water volume from the total energy and mass of the water/steam content (*Lind*,1982). This involves solution of non-linear equations performed by an iterative zero finding procedure (*L g*,1980) used on a linear expression of some auxilliary functions composed by the steam and water density and enthalpy functions. For details, see appendix A. The pressurizer energy and mass balance equations (7.1-2) are then evaluated using the pressurizer spray and outlet flows F_{13} and F_7, heater effect Q_7 and specific energies u_2 and u_7 for primary water and pressurizer outlet flow. For positive outlet flow F_7 the energy u_7 is calculated as enthalpy of pressurizer water, for negative as energy of primary circuit (hot) water.

The pressurizer is treated as a thermal isolated system, and no attempt is used to allow for the limited heat exchange between the system and the reactor. The pressurizer mean temperature T_7 is calculated from the mean pressure alone by the temperature function $T_s(P)$ for saturated steam. The pressurizer heater voltage may be set manually by a control parameter, and may be disconnected entirely by a malfunction parameter (cf. 3.4.6).

3.1.6 Steam Generator model

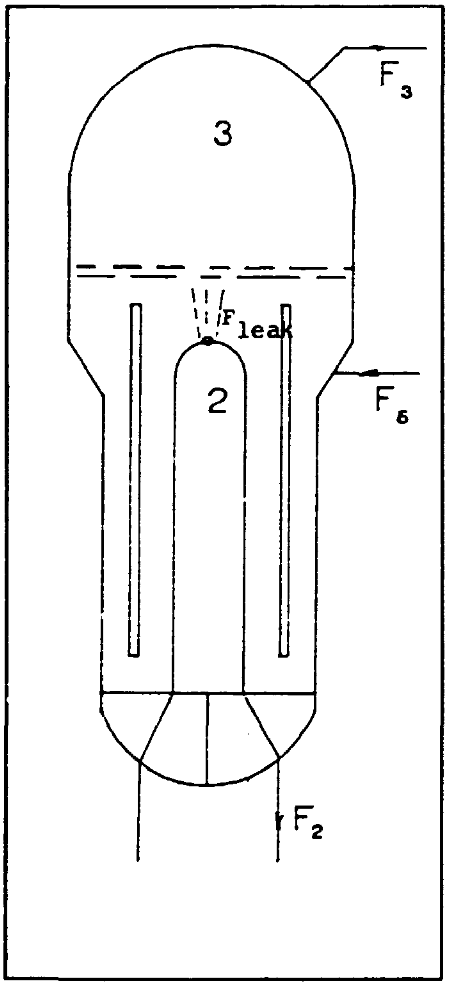

Figure 8. Steam generator model

heat transfer

$$Q_{23} = \alpha_3 K_{23}(T_2 - T_3), \quad \alpha_3 = \frac{V_f}{V_3} \tag{8.1}$$

dynamic equations (tube side)

$$\frac{d}{dt}U_2 = F_2(u_1 - u_2) - Q_{23}, \quad u_1 = \frac{U_1}{M_1}, \quad u_2 = \frac{U_2}{M_2} \tag{8.2}$$

$$M_2 = constant \tag{8.3}$$

dynamic equations (shell side)

$$\frac{d}{dt}U_3 = F_5 u_5 - F_3 u_3 + Q_{23} + F_{leak} u_2 \tag{8.4}$$

$$\frac{d}{dt}M_3 = F_5 - F_3 + F_{leak} \tag{8.5}$$

$$T_3 = T_s(P_3) \tag{8.6}$$

two-phase equations (shell side)

$$U_3 = V_3(\alpha_3 \rho_f(P_3) h_f(P_3) + (1 - \alpha_3)\rho_g(P_3) h_g(P_3)) \tag{8.7}$$

$$M_3 = V_3(\alpha_3 \rho_f(P_3) + (1 - \alpha_3)\rho_g(P_3)) \tag{8.8}$$

The steam generator model is quoted with figure 5. In the tube side only the energy balance equation (5.2) is used as the tube water mass is assumed constant in time (5.3). The shell side is treated analogous to the pressurizer, and the two-phase evaluation routines (cf. appendix B) is used to determine relative water level α_3 and steam pressure P_3. For the malfunction purpose the heating tube is allowed to surpass the water level, in fact a serious accident in a real power plant, and hence the transmitted heat effect are set proportional to both mean temperature difference between tube and shell side and relative water level (5.1). Steam mean temperature T_3 is calculated from the saturated steam temperature function $T_s(P)$. Malfunction capability in the steam generator, representing primary circuit in this connexion, is implemented by the possibility of a steam generator tube leak (cf. 3.4.8).

3.1.7 Condenser model

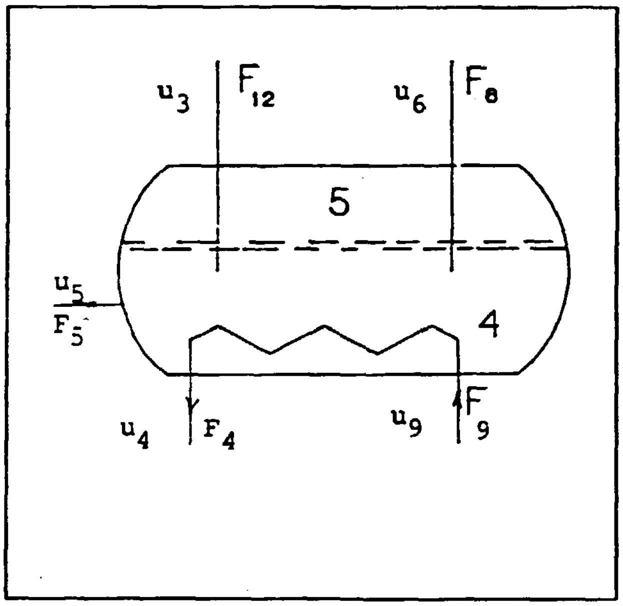

Figure 9. Condenser model

<u>heat transfer</u>

$$Q_{45} = K_{45}(T_4 - T_5) \tag{9.1}$$

<u>dynamic equations (tube side)</u>

$$\frac{d}{dt}U_4 = F_9(u_9 - u_4) - Q_{45} \approx 0 \tag{9.2}$$

$$u_4 = C_pT_4 \qquad u_9 = C_pT_9 \tag{9.3}$$

$$T_4^{(abs)} = \frac{F_9u_9 + K_{45}T_5}{F_9 + K_{45}} \tag{9.4}$$

<u>dynamic equations (shell side)</u>

$$\frac{d}{dt}U_5 = F_{12}u_3 + F_6u_6 - F_5u_5 + Q_{45}, \quad u_3 = h_g(P_3) \tag{9.5}$$

$$\frac{d}{dt}M_5 = F_{12} + F_6 - F_5, \quad u_5 = h_f(P_5) \tag{9.6}$$

$$T_5 = T_s(P_5), \qquad u_6 = \frac{F_{g6}h_g(P_5) + F_{f6}h_f(P_5)}{F_{g6} + F_{f6}} \tag{9.7}$$

two-phase equations (shell side)

$$U_5 = V_5(\alpha_5 \rho_f(P_5) h_f(P_5) + (1 - \alpha_5) \rho_g(P_5) h_g(P_5)) \tag{9.8}$$

$$M_5 = V_5(\alpha_5 \rho_f(P_5) + (1 - \alpha_5) \rho_g(P_5)) \tag{9.9}$$

The condenser is modelled very similiar to the steam generator shell side assuming that both water and steam is present at saturated conditions. The two-phase calculation algorithm used for the steam generator and pressure determination due to the large range applicability of the approximated thermodynamical functions. The equations used for two-phase calculation (9.8-9) and the mass- and energy balance equations (9.5-7) and (9.2-4) are quoted with figure 9. However, the tube side of the condenser is treated different from the steam generator tube assumimg constant energy content as well as constant water mass. This approach prevents the dynamic of the system to degenerate into a stiff system system coping with small characteristic time constants, and hence we replace the dynamical equations with an algebraic equation (9.4) for determination of tube temperature T_4 from shell side temperature T_5, cooling water flow F_9 and specific water energies evaluated from (9.3) expressing proportionality between specific energy and absolute temperature by the heat capacity coefficient C_p= $4.19 \cdot 10^{-3}$ MJ/Kg/oC.

3.1.8 Turbine/Generator model

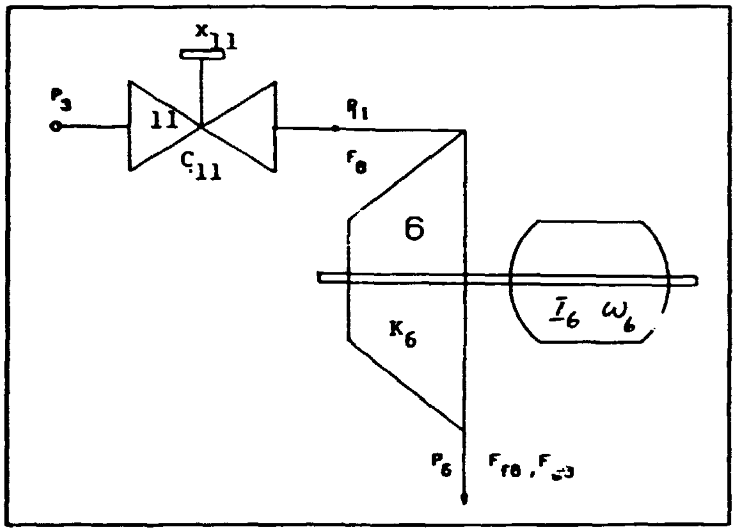

Figure 10. Turbine/Generator model

generator equations

$$\frac{d}{dt}E_{kin} = W_6 - W_e \qquad E_{kin} = \frac{1}{2}I_6\omega_6^2 \tag{10.1}$$

$$W_e = \frac{V^2}{R_6} \tag{10.2}$$

$$V_6 = K\omega_6 \tag{10.3}$$

thermodynamical turbine equations

$$F_6 s_g(P_{11}) = F_{g6} s_g(P_5) + F_{f6} s_f(P_5) \tag{10.4}$$

$$F_6 = F_{g6} + F_{f6} \tag{10.5}$$

$$W_6 = F_6 h_g(P_{11}) - F_{g6} h_g(P_5) - F_{f6} h_f(P_5) \tag{10.6}$$

flow rate balance equation

$$F_6 = K_6(P_{11} - P_5) = x_{11} C_{11}(P_3 - P_{11}) \tag{10.7}$$

Flow rate calculation

$$F_6 = \frac{x_{11} C_{11} K_6}{x_{11} C_{11} + K_6}(P_3 - P_5) \approx x_{11} \frac{C_{11} K_6}{C_{11} + K_6}(P_3 - P_5) \qquad (10.8)$$

The turbine (figure 10) is modelled in a simple way neglecting all dynamic effects (*Lind*,1982). In the turbine flow rate calculation it is then convenient to consider the turbine and the turbine valve as an integrated component combining the turbine valve characteristic equation with the turbine flow rate equation (10.7). Turbine inlet flow F_6 is then calculated using the general control valve model with a »reduced« valve constant composed by the turbine constant K_6 and the valve constant C_{11} (10.8). The turbine outlet flows of saturated steam and water (10.4-5) are then calculated by means of the entropy functions for water and steam assuming ideal isentropic conditions. The mechanical energy W_6 produced is calculated by the energy balance equation (10.6).

The generator equations (10.1-3) simulates the generator as a dynamic system acting as a storage for kinetic energy E_{kin} due to moment of inertia I_6 and shaft angular velocity ω_6. The magnetizing current of the generator is assumed constant in time yielding proportionality between shaft angular velocity and generator output voltage V_6. The voltage is controlled by the power controller component (32) which affects the turbine valve and hence the mechanical turbine energy W_6 produced. The moment of inertia I_6 is estimated such that the generator system manifests a characteristic time period t_0 of about 10 seconds for equalizing a possible difference between electrical energy W_e and turbine energy W_6 with nominal load resistance R_6.

The turbine/generator system is modelled by a malfunction parameter for accidental loss of generator voltage and a control parameter for turbine trip capability (3.4.7).

3.1.9 Volume control tank model

The volume control tank component (8) is modelled as a storage of mass only using the mass balance equation

$$\frac{d}{dt}M_8 = F_{14} - F_8$$

assuming that the specific energy is constant due to thermal coupling between inlet and outlet flows. There is no malfunction capability implemented for the volume control tank.

3.1.10 Lubrication systems

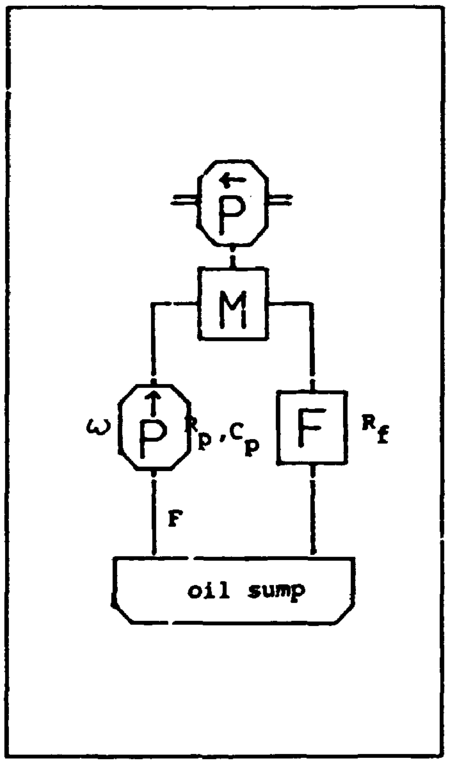

Figure 11. Lubrication systems

Two oil lubrication systems are implemented in the power plant model, one for the primary coolant pump and the other for the feedwater pump. The lubrication system modelled is quoted with figure 11. This model implements a simple oil supply circuit consisting of an oil pump model implemented by use of the general pump model and an oil temperature function. The oil flow rate is estimated from oil pump parameters ω, C_p, R_p and the filter friction constant R_f (11.1). The oil temperature is estimated from the very simplified temperature function (11.2) expressing inverse proportionality between oil flow and temperature. The temperature coefficients are estimated such that oil temperature is about 60 Celcius degree for normal oil flow rate (0.01 Kg/s) and about 500 Celcius degree for stopped flow.

$$F = \frac{C_p \omega}{R_p + R_f} \qquad (11.1)$$

$$T = 15.0^\circ C + \frac{0.5}{F + 10^{-3}} {}^\circ C \qquad (11.2)$$

3.1.11 Filter systems

Besides filter components in the oil lubrication sytem a filter component in the cooling water circuit is implemented. Similiar to the oil filter implementations the cooling water filter is simply modelled by a friction constant added to the pump friction parameter in the cooling water pump flow model. No special malfunction parameter for filter components are implemented in the plant model, but malfunctions due to filter blocking may be achieved assigning appropriate high values to the filter constants.

3.2 Control system representation

3.2.1 Automatic controller models

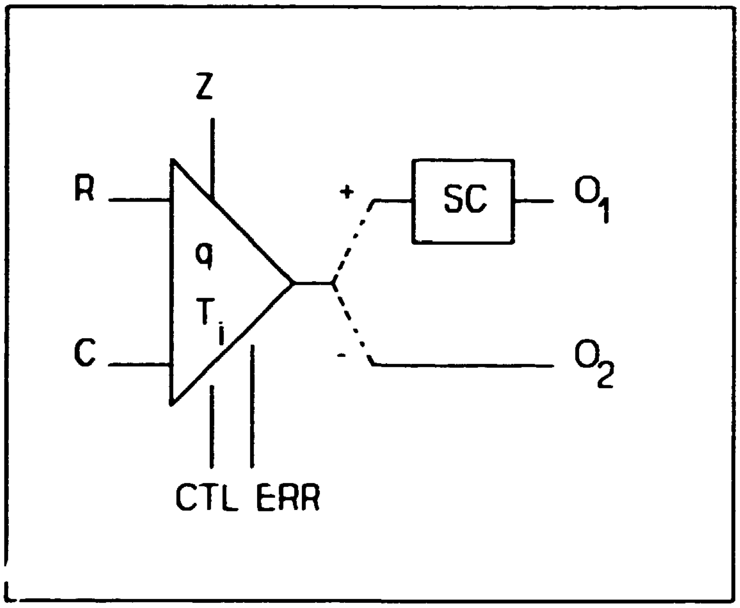

Figure 12. Controller model

The power plant model implements two types of general automatic controllers, a one-output controller used for steam generator level and pressure control and generator voltage control, and a two-output controller used for pressurizer level and pressure control.

Both controllers models are PI (proportional-integral) type controllers with nearly the same function, the two-output controller may be considered an extension of the one-output controller by addition of a switch and a scaling constant.

The controller models include the following parameters (figure 12): a setpoint reference R, controlled input signal C, proportional constant q and reset time constant T_i, state (reset) parameter Z, control signal S and one or two output parameters O_{1-2} . For two-output controllers the switch position is governed by the signs of the control signal S. For malfunction and auto/manual capability the models also include a control parameter and an error parameter. The state variable Z is only changed when the error signal is less tha 20 per cent of the setpoint value, and hence the controller is functioning as a pure proportional controller for large deviances from the setpoint.

Figure 13 summarizes all controllers used in the power plant model with associated controlled and activated process variables.

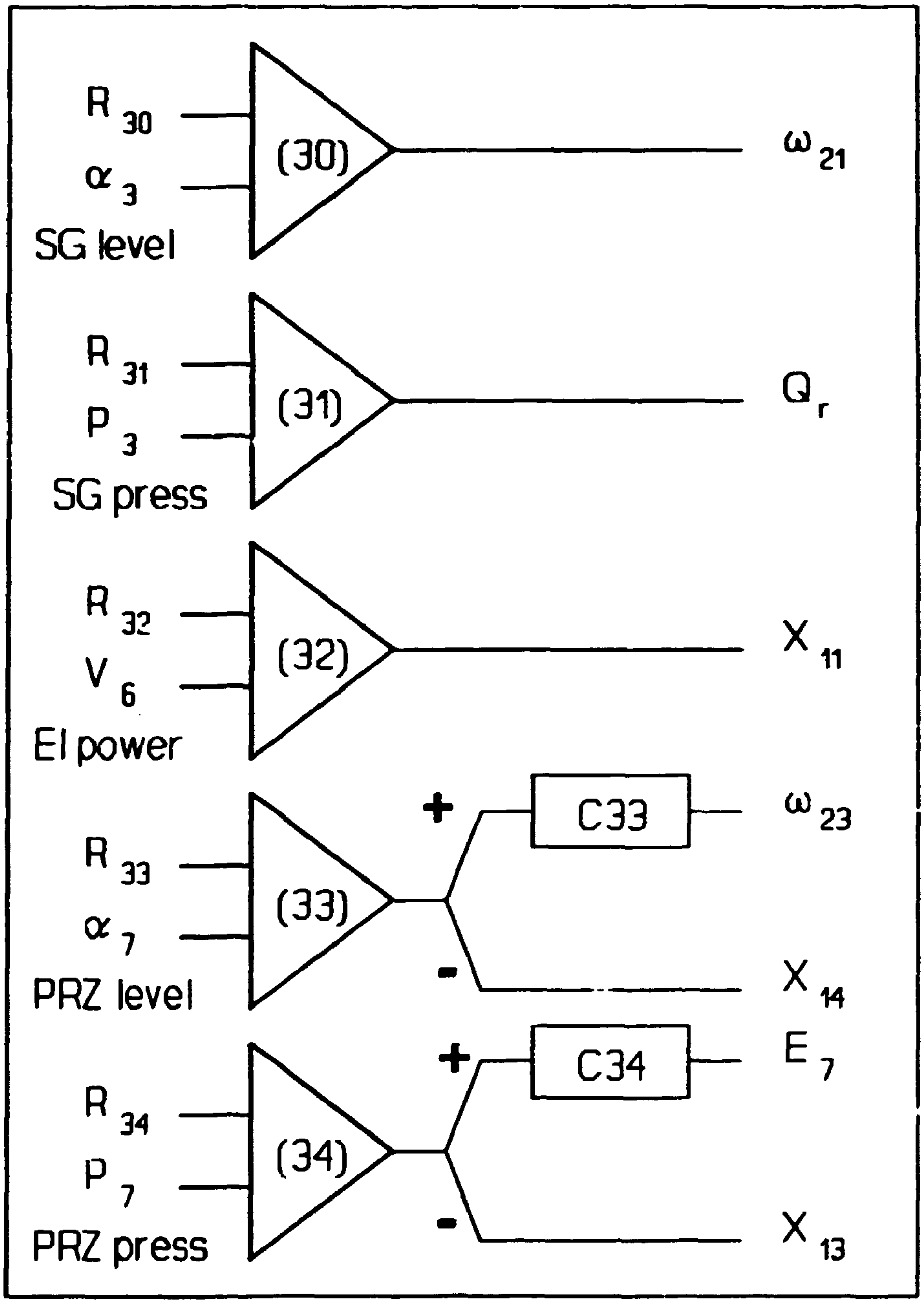

Figure 13. Plant controllers

The internal controller circuit logic common to both controller types is shown in figure 14. Also stated is the two closed control loop transfer functions $H(s)$, estimated from two selected forms for plant transfer functions $F(s)$. These expressions are used for estimation of the controller constants q and T_i. (cf. 3.2.2).

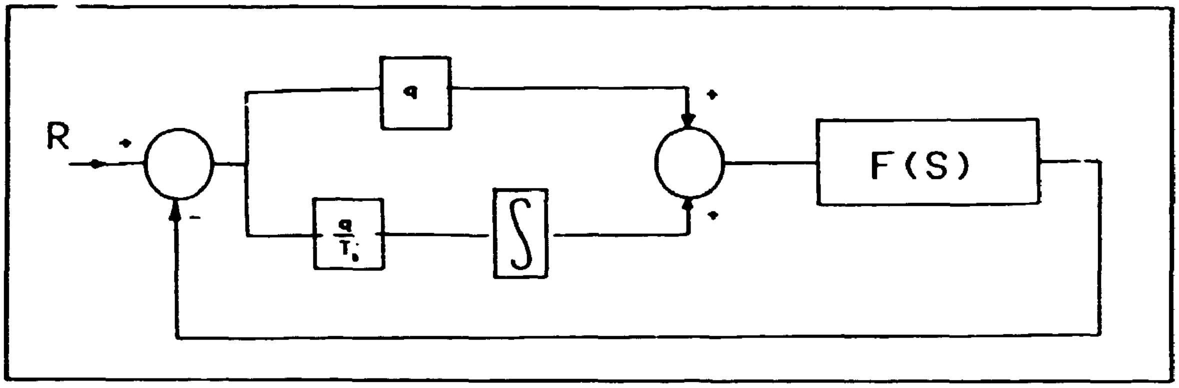

Figure 14. Controller logic

$$F(s) = \frac{K}{s}$$

$$H(s) = \frac{qK(s + \frac{1}{T_i})}{s^2 + qKs + q\frac{K}{T_i}} \qquad (14.1)$$

$$q = \frac{0.87}{Kt}, \quad T_i = 0.87\,t$$

$$F(s) = \frac{K}{1 + t_0 s}$$

$$H(s) = \frac{\frac{qK}{T_i t_0}(sT_i + 1)}{s^2 + \frac{1 + qK}{t_0}s + \frac{qK}{T_i t_0}} \qquad (14.2)$$

$$q = \frac{0.87\frac{t_0}{t} - 1}{K}, \quad T_i = t(0.87 - \frac{t}{t_0})$$

3.2.2 Controller dimensioning

With exception of controller (32) for generator voltage control, the four controllers (30), (31), (33) and (34) for steam generator level, steam generator pressure, pressurizer level and pressurizer pressure control are all dimensioned according to the simplifying main assumptions: all controller loops are mutual independant and the plant transfer function *F(s)* for each controller loop (figure 14) are of the simple type (14.1) or (14.2) corresponding to either linear or exponential shaped time step responses. Naturally this is a heavy simplification as the control circuits are strongly non-linear, and should be considered from a multivariable system point of view, taking mutual influences into account. Estimated plant time response functions due to input unit step functions are leading to the following plant transfer function estimations

Table 3. Transfer function estimation

controller	plant transfer function type	transfer function parameters	switch constant
(30)	K/s	K= $4.7 \cdot 10^{-5}$ sec^{-1}	-
(31)	$K/(1 + t_0 s)$	K= 0.26 bar/MW t_0= 97 sec.	-
(32)	not estimated		
(33)	K/s	K= $-3.8 \cdot 10^{-4}$ sec^{-1}	C_{33}= 1180 rpm
(34)	K/s	K= -0.26 bar/sec	C_{34}= 107 V

These estimations of plant transfer functions does not involve the two-output controller switch constants for controllers (33) and (34) (figure 12) as the negative controller switch positions are used corresponding to changes of valve positions X_{14} for let down flow and X_{13} for spray flow rate. The controller switch constants are determined graphically switching the controllers to positive position and varying the constants such that step responses for unchanged input steps shows positive slopes of the same magnitude. The values for the constants determined in this way are stated in table 3.

The internal controller constants, proportional factor q and reset time T_i should now be estimated from the complex pole configuration of the closed loop transfer function *H(s)* for two cases considered (figure 14). The complex pole configuration depends on estimated values for closed controller loop time constant t (reciprocal loop frequency) and damping of about 30 degrees, we get the formulas in (14.1) and (14.2) for determination of the controller constants.
Table 4 shows the estimated time constants and the evaluated controller constants.

Table 4 - Controller constants

controller	time constant t (estimated)	proportional constant q	reset time constant T_i
(30)	70 sec	526 rpm	121 sec
(31)	60 sec	9.6 MW/bar	73 sec
(32)	10 sec	$12 \cdot 10^{-5}$ V^{-1}	0.05 sec
(33)	100 sec	45.5	173 sec
(34)	90 sec	0.074 bar^{-1}	156 sec

Controller (32) for generator voltage takes up an exceptional position as the dynamics of the generator system (3.1.8) couples to the rest of the plant model in a way too complicated for the simple controller tuning procedure described above, and thus the controller constants in table 4 for this controller are estimated graphically by experiment leading to a reasonably controlled behaviour of the generator voltage.

3.2.3 Reactor rod bank kinetics

The movement of the reactor rod bank is controlled by the control loop depicted in figure 3. Calculating the transfer function for this loop we may estimate the loop constants K_1 and K_2 from the expressions

$$K_1 = \frac{1}{C_1 t_0^2}, \qquad K_2 = 2\zeta C_1 t_0$$

where t_0 is the control loop time constant (recoprocal loop frequency), ζ the damping ratio and C_1 the reactor reactivity coefficient. The expressions are obtained choosing a time constant of 30 seconds, a damping ratio of 0.87 (transfer function pole angles about 30 degrees) and the value of the reactivity coefficient C_1 estimated in appendix A.

3.3 Plant component interaction

The power plant consists of two main loops, the primary coolant loop and the secondary steam line loop. While the steam line flow rates are simple to estimate depending only on the steam line valve position and the feedwater pump velocity, the primary coolant flow rate and pressure calculations is somewhat more intricate.

3.3.1 The primary coolant system approach

The mass balance equations for the primary flow rates are calculated by the follo ·ing expressions derived from figure 15

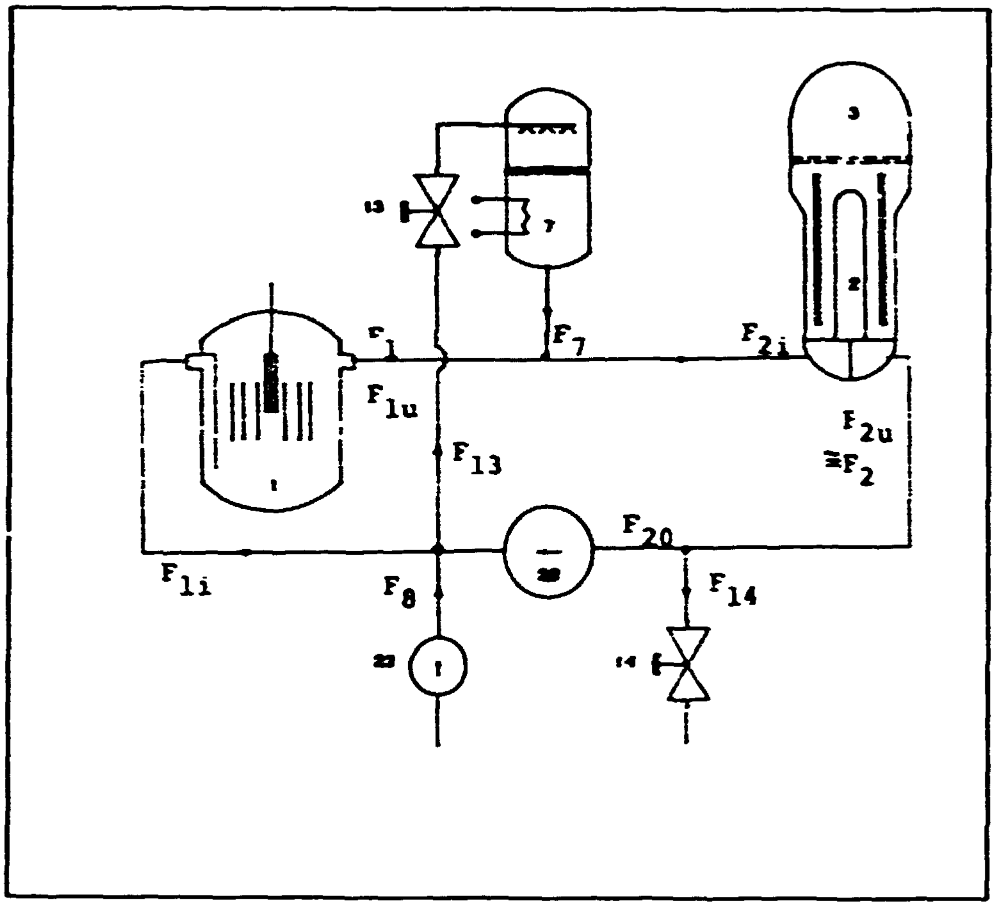

Figure 15. Coolant system, mass and presssure balance

<u>mass balance equations</u>

$$F_{1i} = F_8 + F_{20} - F_{13} \qquad (15.1)$$

$$F_{1u} = F_{1i} + V_1 \frac{d\rho_w}{dT} \frac{dT_1}{dt} \qquad (15.2)$$

$$F_{2u} = F_{20} + F_{14} \qquad (15.3)$$

$$F_{2i} = F_{2u} + V_2 \frac{d\rho_w}{dT} \frac{dT_2}{dt} + F_{leak} \qquad (15.4)$$

$$F_7 = F_{2i} - F_{1u} \qquad (15.5)$$

pressure balance equations

$$P_1 = P_7 + R_1 F_1 \qquad (15.6) \qquad\qquad P_2 = P_7 + R_2 F_2 \qquad (15.7)$$

$$R_1 F_1 + R_2 F_2 + R_{20} F_{20} = C_{20}\omega_{20} + DP_{stat} \qquad (15.8)$$

where

$$DP_{stat} = g(\rho_w(T_2) - \rho_w(T_1))(h_1 + h_2) \qquad (15.9)$$

Equations (15.2) and (15.4) are derived from the general expression

$$V\frac{d}{dt}\rho_w = V\frac{d}{dT}\rho_w\frac{dT}{dt} = F_i - F_u$$

expressing mass flow change for inlet and outlet flow rates for a volume V, assuming quasi stationary pressure conditions, so that specific density $\rho_w(T)$ only depends on temperature T. This equation used for dynamical mass flow contributions for reactor vessel and steam generator tube side water volumes, taking density changes into account, contributes to a more accurate determination of pressurizer flow rate F_7 (15.5).

The model approach also considers the effect of natural coolant circulation due to the U-type shaped flow paths for both steam generator tube and reactor vessel water volume giving the static pressure DP_{stat} for the reactor and steam generator systems (15.9) where $\rho_w(T_2)$ and $\rho_w(T_1)$ denote specific densities of cold and hot coolant water in the reactor legs, and h_1 and h_2 the geometrical heights of the reactor vessel and steam generator tube.

The pressure balance equation in the coolant system (15.8) is obtained from the linearized pump and valve characteristics and the pressure drops through reactor vessel and steam generator tube using some estimated friction coefficients R_1 and R_2 (15.6-7). Pressure and flow variables in the coolant system can now be now determined in sequence.

Charge and release flow rates F_8 and F_{14} (16.1-2) are estimated by the charging pump and let down valve using the general pump and control valve models with pressurizer pressure P_7 alone, neglecting the (minor) pressure drops through the other coolant loop components. This approximation alleviates the pressure calculation avoiding implicit equation solving strategies.

$$F_8 = \frac{(C_{23}\omega_{23} - P_7)}{R_{23}} \qquad (16.1)$$

$$F_{14} = x_{14} C_{14} P_7 \qquad (16.2)$$

Coolant pump flow rate F_{20} (16.3) is determined from (15.8) and calculated by the general pump flow model using a reduced pressure head DP_{20}' (16.5) and pump friction parameter R_1' (16.4) depending on the state of the spray flow valve and charging components. The linearized pump and valve characteristics contribute much for simplicity in derivation of these expressions.

$$F_{20} = \frac{(C_{20}\omega_{20} - DP_{20}')}{R_1' + R_2 + R_{20}} \tag{16.3}$$

$$R_1' = \frac{R_1}{1 + x_{13}C_{13}R_{20}} \tag{16.4}$$

$$DP_{20}' = R_1'F_8 + R_2F_{14}DP_{stat} \tag{16.5}$$

where

$$DP_{stat} = g(\rho_w(T_2) - \rho_w(T_1))(h_1 + h_2) \tag{16.6}$$

Next the spray flow rate F_{13} (16.7) is calculated using the control valve model with pressure drop determined from (16.8)

$$F_{13} = x_{13}C_{13}DP_{13} \tag{16.7}$$

where

$$DP_{13} = R_1F_1 = R_1'(F_8 + F_{20}) \tag{16.8}$$

and then the reactor and steam generator flow rates F_1 and F_2 are calculated using (16.9) and (16.10).

$$F_1 = F_{20} + F_8 - F_{13} \tag{16.9}$$

$$F_2 = F_{20} + F_{14} - F_{leak} \tag{16.10}$$

Finally the pressurizer flow F_7 is calculated from (16.11) derived from (15.5).

$$F_7 = F_{13} + F_{14} - F_8 + V_1 \frac{d\rho_w}{dT}\frac{dT_1}{dt} + V_2 \frac{d\rho_w}{dT}\frac{dT_2}{dt} \tag{16.11}$$

where

$$\begin{aligned} \frac{dT_1}{dt} &= \frac{1}{M_1 C_p}\frac{dU_1}{dt} \\ \frac{dT_2}{dt} &= \frac{1}{M_2 C_p}\frac{dU_2}{dt} \end{aligned} \tag{16.12}$$

The temperature gradients in these formulas are approximated by the expressions (16.12) using proportionality between absolute temperature and total energy U

$$U = MC_pT \tag{16.13}$$

where $C_p = 4.19 \cdot 10^{-3}$ MJ/Kg/oC is the heat capacity coefficient for constant pressure.

This temperature approximation is considered sufficient accurate for calculation of these gradients, although the nominal temperature for the primary coolant falls outside the domain for this equation.

3.3.2 Activity concentration propagation

Figure 16 shows the secondary loop of the plant together with the equations for calculation of activity concentration propagation in the steam line and condenser in case of a steam generator tube leak (cf. 3.4.8). The activity concentration in a specific component is defined as the relative mass ratio between the mass of the present coolant leakage and the total inventory mass. Equations (16.1) and (16.2) determine the activity state variables C_3 and C_5 describing the dynamics of activity concentrations in the steam generator and condenser shell side, and equations (16.3-5) determine the activities in the turbine C_6, safety valve out flow C_{10} and bypass valve C_{12}.

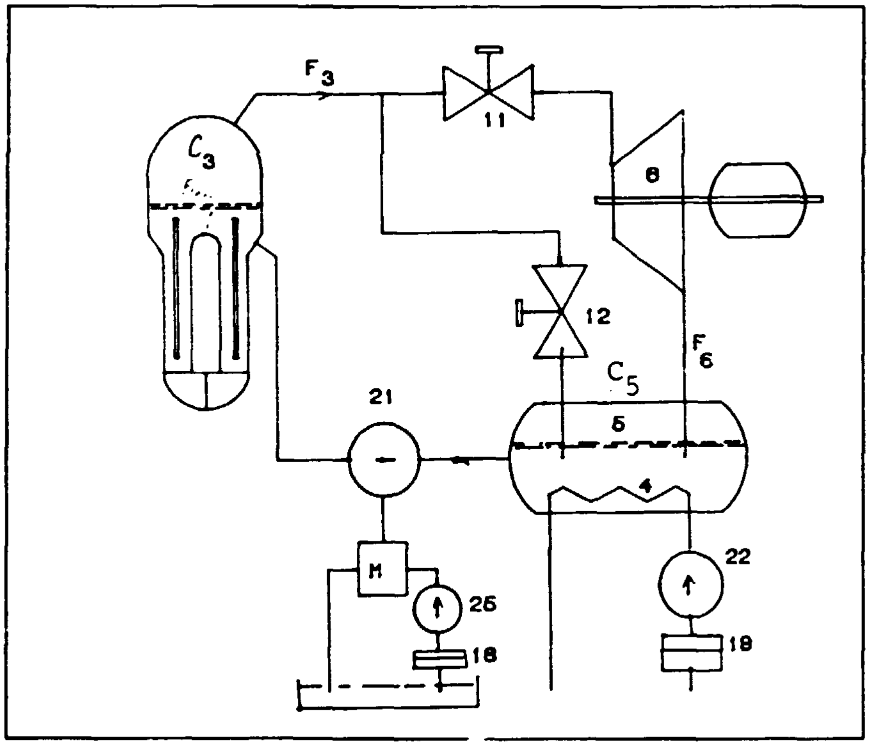

Figure 16. Secondary steam line loop

<u>activity concentrations</u>

$$\frac{d}{dt}C_3 = \frac{(C_5 - C_3)F_5 + \gamma_2 F_{leak}}{M_3} \qquad (16.1) \qquad\qquad \gamma_2 = \begin{cases} 1 & \text{for } F_{leak} \geq 0 \\ C_3 & \text{for } F_{leak} < 0 \end{cases}$$

$$\frac{d}{dt}C_5 = (C_3 - C_5)\frac{F_3}{M_5} \qquad (16.2)$$

$$C_6 = C_3$$

$$C_{10} = C_3 \qquad (16.3)$$

$$C_{12} = C_3$$

3.4 Malfunction and operator control capabilities.

The general component models for valves, pumps and controllers include two real valued process parameters, a control parameter for auto/manual switching and an error parameter for malfunction capability. The control parameters are intended for manual setting of process variables, e.g. setting of valve positions, pump velocities and controller output values, while the error parameters should be used to introduce disturbances to these values. Activation of malfunction and operator control is performed through the actual settings of error and control parameters. The general principle is that parameter values belonging to the unit interval (positive or negative) should be scaled to the actual control or malfunction process variables values while values outside the unit interval are ignored by the components.
The following table states typical control and malfunction possibilities and the relevant process parameters involved (cf. appendix E).

Control valves	
- valve failed close/intermediate/open	CTL11-14
- manual valve position	CTL11-14
- accidental operating	ERR11-14
Safety valves	
- valve failed close/intermediate/open	CTL10,15
Automatic controllers	
- controller failed low/intermediate/high	CTL30-34
- manual output control	CTL30-34
- accidental selecting	ERR30-34
Pumps	
- manual speed control	CTL20-25
- loss of power	CTL20-25
- pump failed off/intermediate/on	CTL20-25
- accidental operation	ERR20-25
Reactor	
- failure in control rod bank position reference	ERR1
- reactor trip (control rod bank drop)	CTL1
- failure in control rod bank speed	ERR35
- manual control rod bank speed control	CTL35
Pressurizer heater	
- loss of power	CTL7
- manual power control	CTL7
- accidental operation	ERR7
Turbine/generator	
- accidental generator voltage	ERR6
- turbine trip	CTL6
Steam generator tube leak	
- leak size parameter	CLK2

3.4.1 Control valves

The general control valve model includes two real valued process parameters, an error parameter for malfunction capability (accidental operating valve) and a control parameter for auto/manual switching (e.g. valve getting stuck). A non negative control parameter value in the unit range is transferred to the valve position variable while other values are ignored. An error parameter value in the unit range increments the actual valve position value with this relative amount while other values are ignored.

3.4.2 Safety valves

The safety valve model includes only a control parameter for accidental manual selection, simulating a failed open, failed intermediate or failed closed valve. More complex malfunctions such as failure to reclose after opening is not possible with the actual model although it is by far the most common type of safety valve failure. There is no mechanism either for simulating a wrong setpoint. Similiar to the control valve only non negative parameter values in the unit range have any effect on the valve.

3.4.3 Automatic controllers

Like the control valve component the automatic controller components contain real valued parameters for malfunction handling and auto/manual control. The intension is that it should be possible to switch any automatic operating controller or failed controller to manual mode thus allowing a failed controller output to be manually reset. In this manual mode it should then be possible to control the component to any of its states even if these are not the desired ones for the process condition (e.g. primary pump off with reactor operating). The error parameter in the unit range modifies the controller outputs with this relative amount while other values are ignored. The control parameter are capable of generating the full range of controller output, so that values are scaled to output values. Control parameters for two-output controllers may have both positive and negative values due to the switching operating prinsiple (cf. 3.2.1).

3.4.4 Pumps

Similiar to the control valve component the general pump component model contain real valued parameters for malfunction capability (e.g. pump failed at intermediate speed) as well as auto/manual selection (e.g. loss of power, on/off selection for fixed-speed pumps and manual speed control for variable-speed pumps). The model scales non negative control parameter values from the unit range to pump speed to the range from zero to maximal pump speed allowed. Positive and negative values of the error parameter in the unit range increments the pump velocity with this relative amount while other values are ignored.

3.4.5 Reactor

In the reactor model the control rod bank position mechanism may be disturbed either by changing the control rod reference value x_r corresponding to disturbance of critical reactor conditions, or by changes in the control rod bank velocity w_1 (cf. 3.1.1). Position reference disturbance is achieved through small signed values in the unit range of the error parameter ERR1, and accidental reference position through non negative setting of the control parameter CTL1. Control rod bank velocity disturbance is achieved through analogous settings of the parameters CTL35 and ERR35. Notice that decreasing values is equivalent to a rod withdrawal and that incresing values correspond to rod insertion so that reactor trip may be simulated by setting these parameters to unity. Instantaneous rod drop may be simulated setting the rod position state variable X1 and speed variable W1 to zero.

3.4.6 Pressurizer heater

The pressurizer heater is modelled with a power control parameter CTL7 and a heater disturbance parameter ERR7. Non negative control parameters are scaled to heater voltage from zero to maximal heater voltage. Small signed values in the unit range of the error parameter introduce heater disturbances.

3.4.7 Turbine/Generator

Generator output voltage V6 may be disturbed due to some generator malfunction by small signed values in the unit interval of the error parameter ERR6 and a turbine trip with loss of generator power as a consequence is signalled by non negative values of the control parameter CTL6. The model also provides for automatic turbine trip on generator overspeed, i.e. when the speed exceeds a maximal turbine speed. There is no malfunction parameter facility incorporated to deal with disconnection of load or load re-engagement, but the load resistance R6 may be changed in the model data base.

3.4.8 Primary circuit leakage

The simulator offers the ability to simulate a single leak in the steam generator tube. A leak is modelled in a very simple way setting the leak flow proportional to the presssure difference between tube and shell side of the steam generator. The magnitude of the leak coefficient CLK2 will depend on the leak size and may be estimated accodingly.

3.5 Physical alarms

The computer model approach to the real physical power plant and the selected numerical methods used in the implementation involve that there may be process parameter conditions which transfer the system to states beyond physical reality. These conditions may either arise due to violations of some physical limitations, - e.g. a full or empty tank, temperature arguments outside defined ranges etc. - or they may be caused by numerical algorithms implemented, e.g. a convergence failure in a root finding procedure. Physical alarms stops the model and generate messages in clear text with specification of the alarm type and the involved model components - e.g. »Pressurizer, High temperature limit« and calls for operator interveniance.

3.6 Interlock and safety systems

There is no automatic interlock and safety systems implemented in the power plant model as interlock and safety functions should be performed by a separate safe module external to physical plant model. Reactor trip should be trigged by high temperature, high power or loss of coolant flow etc. However, the only exception is that the turbine may trip itself due to overspeed (cf. 3.4.7).

4 References

Achieser, N.I. (1956). Theory of Approximation. New York.

Brent, R.P. (1973). Algoritms for Minimization without Derivation. Prentice Hall.

Fehlberg, E. (1969). Low order classical Runge-Kutta formulas with step size control and their application to some heat transfer problems. Nasa report TR R-315. Alabama.

Højberg K.S. (1982). Power Plant Model for Display Experiments. Risø N-24-82.

Hunt G. (1984). Operator Control and Malfunction Capabilities. Lit no. 320(3.3), note 2657. Halden.

Keeman, J. & Keyes (1948). Thermodynamic properties of Steam. John Wiley & Sons, New York.

Lang-Rasmussen, O. (1980).The Algol procedure ZERO, RMA Risø.

Lind, M. (1982). GNP - A Power Plant Model for Man-Machine experiments. Risø N-23-82.

VDI Wasserdampftafeln, 6. auflage. Springer Verlag 1963.

Wiese, R. (1969). The Algol procedure RATCHEB, SA-129. Reactor Physics Department, Risø.

A Neutron dynamics and reactor effect

The basic equations is the one-dimensional kinetic equations for the concentration of prompt neutrons n and delayed neutrons C

$$\frac{dn}{dt} = \frac{\rho-\beta}{l}n + \lambda C \tag{A1}$$

$$\frac{dC}{dt} = -\lambda C + \frac{\beta}{l}n \tag{A2}$$

where ρ denote the reactor reactivity, l neutron mean life time and β fraction of total neutrons which is delayed neutrons with decay constant λ.

Equalizing equation (A1) to zero, assuming that the prompt neutron profile stabilizes few milliseconds after a pertubation, we get from (A1) and (A2) the simplified first order differential equation for the neutron concentration

$$\frac{dn}{dt} = \frac{\lambda\rho}{\beta-\rho}n \tag{A3}$$

In general the reactivity ρ depends on several reactor parameters such as control rod position, reactor mean temperature and boron concentration. However, in the computer model we let the reactivity depend only upon reactor rod position x_1 and further the following approximation is made

$$\frac{\lambda\rho}{\beta-\rho} = C_1(x_1-x_0) \tag{A4}$$

as the reactivity is vanishing for $x_1 = x_0$, where x_0 is the rod position corresponding to critical reactor condition.

Using that the reactor effect Q_1 is proportional to the neutron concentration we finally get the reactor effect equation used in the computer model

$$\frac{dQ_1}{dt} = C_1(x_1-x_0)Q_1 \tag{A5}$$

From (A4) the reactivity constant C_1 is estimated to 0.18 sec^{-1} setting $\lambda = 0.08$ sec, $\beta = 0.075$ and $\rho = \rho_{max} = 0.004$ for $x_1 - x_0 = 0.5$.

B Two-phase mixture calculation

For the pressurizer, steam generator and condenser, we have from (Lind,1982) the following two-fase relation between total mass M_t, total volume V_t, water level α and pressure P

$$M_t = V_t((\rho_f(P) - \rho_g(p))\alpha + \rho_g(p))$$

$$U_t = V_t((\rho_f(P)h_f(P) - \rho_g(P)h_g(P))\alpha + \rho_g(P)h_g(P))$$

where ρ_f, h_f, ρ_g, h_g denote density and enthalphy of saturated resp. unsaturated water.

Defining

$$\rho = \frac{M_t}{V_t} \qquad \text{and} \qquad u = \frac{U_t}{V_t}$$

we get the relations

$$\rho = (\rho_f(P) - \rho_g(P))\alpha + \rho_g(P) \tag{B1}$$

$$u = (\rho_f(P)h_f(P) - \rho_g(P)h_g(P))\alpha + \rho_g(P)h_g(P) \tag{B2}$$

By elimination of level α we get

$$\frac{\rho - \rho_g(P)}{u - \rho_g(P)h_g(P)} = \frac{\rho_f(P) - \rho_g(P)}{\rho_f(P)h_f(P) - \rho_g(P)h_g(P)} \tag{B3}$$

Defining the functions ψ_1 and ψ_2 by

$$\psi_1(P) = \frac{\rho_f(P)h_f(P) - \rho_g(P)h_g(P)}{\rho_f(P) - \rho_g(P)}$$

$$\psi_2(P) = \frac{\rho_f(P)\rho_g(P)(h_f(P) - h_g(P))}{\rho_f(P) - \rho_g(P)}$$

equation (B4) reduces to the equation

$$\rho\,\psi_1(P) + \psi_2(P) = u \tag{B4}$$

As the functions ψ_1 and ψ_2 only depends on thermodynamic functions they are approximated by rational Chebyshev functions in the same way as the other steam and water functions used, thus saving computer time in solution of equation (B4).

Given mean density ρ and volume specific energy u, the pressure P is calculated from (B4) by a bisection algoritm (*Lang,1980*).

When pressure P is calculated the relative water volume is then calculated from (B1) as

$$\alpha = \frac{\rho - \rho_g(P)}{\rho_f(P) - \rho_g(P)}$$

In the pressure range from 60 bar to 200 bar we have with an accuracy better than 1 per cent the second order apprximations

$$\psi_1(P) = b_{21}P^2 + b_{11}P + b_{01}$$
$$\psi_2(P) = b_{22}P^2 + b_{21}P + b_{02}$$

and hence the equation (B4) can be solved explicit yielding

$$P_{expl} = \frac{\sqrt{(\rho b_{11} + b_{12})^2 - 4(\rho b_{21} + b_{22})(\rho b_{01} + b_{02} - u)} - (\rho b_{11} + b_{12})}{2(\rho b_{21} + b_{22})}$$

The two-phase calculation is performed by the routine *TWOFAS* in the computer model.

C Numerical integration strategy

The numerical solution method chosen for the approximate integration of a system of first-order differential equations

$$\frac{d\vec{y}}{dt} = \vec{g}(\vec{y},t)$$

is the second order two point Runge-Kutta-Heun integration formula

$$\vec{y}_1 = \vec{y}_0 + \frac{1}{2}(\vec{k}_1 + \vec{k}_2)$$

with

$$\vec{k}_1 = \vec{g}(\vec{y}_0,t_0)\Delta t$$

$$\vec{k}_2 = \vec{g}(\vec{y}_0+\vec{k}_1,t_0+\Delta t)\Delta t$$

For the local per step approximation error vector we get

$$\vec{E} = \vec{y}_1 - \vec{y}(t_1) \approx \frac{1}{2}(\vec{k}_2 - \vec{k}_1)$$

In the integration procedure we use an adaptive change of the integration step size *DT* to ensure that at least local per step errors remain within specified bounds. Given the per step truncation error estimate vector coordinates $E^{(i)},\ i = 1,\dots,n$ we halve or double *DT* if the maximum relative fractional error

$$\max_i \left| \frac{E^{(i)}}{\left|y_1^{(i)}\right| + \left|y_1^{(i)} - y_0^{(i)}\right| + 1} \right| ,\ i = 1,\dots,n$$

falls outside an interval with upper bound *EMAX* and lower bound *EMIN*.

To avoid possible waste of computer time we also specify a minimum value *DTMIN* below which *DT* is no longer halved. We also set an upper bound *DTMAX*, typically equal to the communication interval, i.e. the time interval between successive instants of process state variable estimations.

Finally to avoid continuously halving or doubling of *DT*, the integration routines prevent *DT* from doubling if it was just halved during the last step and vice versa.

The values of *EMAX*, *EMIN*, *DTMAX*, *DTMIN* and initial setting of *DT* is defined in the model input data file.

D Thermodynamical approximations

In the following tables a rational function

$$R_{n,m} = \frac{a_n x^n + a_{n-1} x^{n-1} + \dots + a_0}{b_m x^m + b_{m-1} x^{m-1} + \dots + b_0}$$

with nominator polynomial degree n and denominator polynomial degree m is represented by the abbreviation in notation

$$R_{n,m} = [a_n, a_{n-1}, \dots, a_0] \,/\, [b_m, b_{m-1}, \dots, b_0]$$

All polynomials or rational functions are derived from Chebyshev approximations (ref.[7]) and hence all arguments must be transformed to the unit interval [0,1] before calculation of the expressions.

Figure D.1 Density of saturated water $\rho_f(P)$ [Kg/m^3]

pressure range (bar)	degree	rational Chebyshev approximation
0.01 - 0.2	1,0	[-8.320, 990.0] / [1]
0.2 - 2.0	2,0	[6.975, -19.13, 956.2] / [1]
2.0 - 200.0	2,3	[-262.4, 266.3, 765.5] / [-0.2095, 0.6434, 1.105]

Figure D.2 Density of saturated steam $\rho_g(P)$ [Kg/m^3]

pressure range (bar)	degree	rational Chebyshev approximation
0.01 - 0.2	2,1	[$2.142 \cdot 10^{-2}$, $8.681 \cdot 10^{-2}$, $7.004 \cdot 10^{-2}$] / [0.3898, 1.000]
0.2 - 2.0	2,1	[0.1385, 0.6844, 0.6341] / [0.3141, 1.000]
2.0 - 110.0	3,0	[-0.3373, 0.8430, 3.272, 29.02, 28.06] / [1]
110 - 200	3,0	[2.575, 4.629, 9.500, 45.30, 98.82] / [1]

Figure D.3 Enthalpy of water (unsaturated) $h_w(T)$ [MJ/Kg]

temp. range (°C)	degree	rational Chebyshev approximation
10 - 350	2,1	[-0.4130, 0.2205, 7.267·10⁻³] / [-0.6481, 1.000]

Figure D.4 Enthalpy of saturated water $h_f(P)$ [MJ/Kg]

pressure range (bar)	degree	rational Chebyshev approximation
0.01 - 0.2	2,2	[8.481·10⁻², 0.2564, 0.1751] / [0.1958, 0.9725, 0.9021]
0.2 - 2.0	2,1	[2.120·10⁻², 0.3422, 0.4268] / [0.5773, 1.000]
2.0 - 200.0	2,3	[0.9973, 2.139, 1.143] / [-0.1097, 0.3644, 1.289, 0.8178]

Figure D.5 Enthalpy of saturated steam $h_w(T)$ [MJ/Kg]

pressure range (bar)	degree	rational Chebyshev approximation
0.01 - 0.2	2,0	[-2.974·10⁻², 4.203·10⁻², 2.590] / [1]
0.2 - 2.0	2,0	[-2.400·10⁻², 4.400·10⁻², 2.680] / [1]
2.0 - 200.0	2,2	[-1.338, 1.592, 3.290] / [-0.4132, 0.6600, 1.2067]

Figure D.6 Entropy of saturated water $s_f(P)$ [MJ/Kg/°C]

pressure range (bar)	degree	rational Chebyshev approximation
0.01 - 0.2	2,2	[2.814·10⁻⁴, 8.573·10⁻⁴, 5.879·10⁻⁴] / [0.2086, 0.9862, 0.8957]
0.2 - 2.0	2,2	[5.624·10⁻⁵, 1.053·10⁻³, 1.327·10⁻³] / [0.6019, 1.000]
2.0 - 200.0	2,2	[8.968·10⁻⁴, 3.957·10⁻⁴, 3.177·10⁻³] / [0.0996, 0.9733, 0.9502]

Figure D.7 Entropy of saturated steam $s_g(P)$ [MJ/Kg/°C]

pressure range (bar)	degree	rational Chebyshev approximation
0.01 - 0.2	1,1	$[4.924\cdot10^{-3}, 8.117\cdot10^{-3}] / [0.6436, 1.000]$
0.2 - 2.0	1,1	$[3.578\cdot10^{-3}, 7.319\cdot10^{-3}] / [0.5266, 1.000]$
2.0 - 200.0	2,2	$[-7.262\cdot10^{-4}, 4.387\cdot10^{-3}, 5.722\cdot10^{-3}] / [-3.3896\cdot10^{-2}, 0.8974. 1.0170]$

Figure D.8 Temperature of saturated steam $T_s(P)$ [MJ/Kg/°C]

pressure range (bar)	degree	rational Chebyshev approximation
0.01 - 0.2	2,2	[19.95, 61.05, 41.97] / [0.1914, 0.9664, 0.9043]
0.2 - 2.0	2,2	[23.43, 104.72, 95.83] / [0.1164, 0.8145, 0.9418]
2.0 - 200.0	2,2	[143.3, 405.1, 266.7] / [0.2833, 1.101, 0.8584]

Figure D.9 Water density gradient $\frac{d}{dt}\rho_w(T)$ [Kg/m³/°C]

temp range (°C)	degree	rational Chebyshev approximation
150 - 360	3,2	[0.2048, 0.3806, -0.3059, -1.787] / [-0.3589, -0.5416, 1.180]

E Power plant process variables

Table 5 - Process state variables

Q1	reactor nuclear effect [MW]
UT1	reactor energy [MJ]
UT2	steam generator tube side energy [MJ]
UT3	steam generator shell side energy [MJ]
M3	steam generator shell side mass [Kg]
UT5	condenser energy [MJ]
M5	condenser mass [Kg]
UT7	pressurizer energy [MJ]
M7	pressurizer mass [Kg]
M8	volume control tank mass [Kg]
Z30	steam gen. level ctrl. reset signal [RPM]
Z31	steam gen. press ctrl. reset signal [MW]
Z32	power controller reset signal [0,1]
Z33	pressurizer level ctrl. reset signal [-1,1]
Z34	pressurizer press ctrl. reset signal [-1,1]
CO3	steam generator activity concentration [0,1]
CO5	condenser activity concentration [0,1]
EM6	turbine generator kinetic energy [MJ]
X1	reactor control rod position [0,1]

Table 6. Process paramerers

DP10	steam generator safety valve pressure setpoint [bar]
DP15	pressurizer safety valve pressure setpoint [bar]
REF1	control rod setpoint [0,1]
REF30	steam generator level controller setpoint [0,1]
REF31	steam generator pressure controller setpoint [bar]
REF32	power controller setpoint [V]
REF33	pressurizer level setpoint [0,1]
REF34	pressurizer pressure setpoint [bar]
CTL1	reactor trip status [0,1]
CTL6	turbine/generator trip status [0,1]
CTL7	pressurizer heater auto/manual status [0,1]
CTL11	turbine valve auto/manual status [0,1]
CTL12	turbine bypass valve auto/manual status [0,1]
CTL13	pressurizer spray control valve auto/manual status [0,1]
CTL14	volum control valve auto/manual status [0,1]
CTL20	reactor cooling pump auto/manual status [0,1]
CTL21	feedwater pump auto/manual status [0,1]
CTL22	cooling water pump auto/manual status [0,1]
CTL23	volume control pump auto/manual status [0,1]
CTL30	steam generator level controller auto/manual status [0,1]

Table 6. Process parameters (continued)

CTL31	steam generator pressure controller auto/manual status [0,1]
CTL32	turbine power controller auto/manual status [0,1]
CTL33	pressurizer level controller auto/manual status [0,2]
CTL34	pressurizer pressure controller auto/manual status [0,2]
CTL35	reactor control rod drive auto/manual status [0,2]
ERR1	reactor control rod error status [-1,1]
ERR6	turbine/generator on/off error flag [-1,1]
ERR7	pressurizer heater power on/off error flag [-1,1]
ERR10	steam generator safety valve error status [-1,1]
ERR11	turbine valve error status [-1,1]
ERR12	turbine bypass valve error status [-1,1]
ERR13	pressurizer spray valve error status [-1,1]
ERR14	volume control valve error status [-1,1]
ERR15	pressurizer safety valve error status [-1,1]
ERR20	reactor cooling pump power error status [-1,1]
ERR21	feedwater pump power error status [-1,1]
ERR22	cooling water pump power error status [-1,1]
ERR23	volume control pump power error status [-1,1]
ERR30	steam generator level controller error status [-1,1]
ERR31	steam generator pressure controller error status [-1,1]
ERR32	turbine power controller error status [-1,1]
ERR33	pressurizer level controller error status [0,2]
ERR34	pressurizer pressure controller error status [0,2]
ERR35	reactor control rod drive error status [0,2]
ERR24	reactor cooling system oil pump power status [-1,1]
ERR25	feedwater system oil pump pover status [-1,1]

Table 7. Process variables

P1	reactor pressure [bar]
P2	steam generator tube side pressure [bar]
P3	steam generator shell side pressure [bar]
P5	condenser shell side pressure [bar]
P7	pressurizer pressure [bar]
P8	volume control tank pressure [bar]
P11	turbine valve outlet pressure [bar]
DP11	turbine valve pressure difference [bar]
T1	reactor temperature [oC]
T2	steam generator tube side temperature [oC]
T3	steam generator shell side temperature [oC]
T4	condenser tube side temperature [oC]
T5	condenser shell side temperature [oC]
T7	pressurizer temperature [oC]
T24	reactor cool system oil pump temperature [oC]
T25	feedwater system oil pump temperature [oC]
T8	volume control tank temperature [oC]
T9	condenser inlet temperature [oC]
u1	reactor specific energy [MJ/Kg]
u2	steam generator tube side specific energy [MJ/Kg]
u3	steam generator shell side specific energy [MJ/Kg]
u4	condenser tube side specific energy [MJ/Kg]
u5	condenser shell side specific energy [MJ/Kg]
u6	turbine outlet specific energy [MJ/Kg]
u7	pressurizer outlet specific energy [MJ/Kg]
u9	condenser tube side inlet specific energy [MJ/Kg]
F1	reactor outlet flow [Kg/sec]
F2	steam generator tube side outlet flow [Kg/sec]
F3	steam generator shell side outlet flow [Kg/sec]
F4	condenser tube side out flow [Kg/sec]
F5	condenser shell side out flow [Kg/sec]
F6	turbine flow [Kg/sec]
F7	pressurizer out flow [Kg/sec]
F8	volume control tank out flow [Kg/sec]
F9	condenser tube side in flow [Kg/sec]
F10	steam line safety valve flow [Kg/sec]
F12	bypass flow [Kg/sec]
F13	pressurizer spray flow [Kg/sec]
F14	volume control tank in flow [Kg/sec]
F15	pressurizer svalve flow [Kg/sec]
F16	reactor cool pump flow [Kg/sec]
F24	reactor cool system oil pump flow [Kg/sec]
FLK2	steam generator tube side lkg flow [Kg/sec]
W1	reactor crtl rod speed [s-1]
X11	turbine valve pos [0,1] [0,1]
X12	turbine bypass valve pos [0,1]
X13	pressurizer spray valve pos [0,1]
X14	volume control tank valve pos [0,1]

Table 7. Process variables (continued)

AC3	activity concentration in flow F3 [0,1]
AC5	activity concentration in flow F5 [0,1]
AC6	activity concentration in flow F6 [0,1]
AC10	activity concentration in flow F10 [0,1]
AC12	activity concentration in flow F12 [0,1]
E7	pressurizer heater voltage [V]
Q7	pressurizer heat effect [MW]
Q23	steam generator transmission effect [MW]
Q45	condenser transmisson effect [MW]
ALFA3	steam generator water level [0,1]
ALFA5	condenser water level [0,1]
ALFA7	pressurizer water level [0,1]
ALFA8	volume control tank water level [0,1]
C11	turbine valve constant [Kg/sec.bar]
C12	bypass flow valve constant [Kg/sec.bar]
C13	pressurizer spray valve constant [Kg/sec.bar]
C14	volume control tank flow valve constant[Kg/sec.bar]
OM20	reactor cool pump angular velocity [rpm]
OM21	feedwater pump angular velocity [rpm]
OM22	cooling water pump angular velocity [rpm]
OM23	volume control tank pump angular velocity [rpm]
OM24	reactor cool system oil pump angular velocity [rpm]
OM6	generator angular velocity [rpm]
R6	turbine/generator load resistance [ohm]
V6	turbine/generator potential [V]
W6	turbine effect [MW]
WE6	turbine generator electric load [MW]
QR1	reactor effect demand [MW]

Table 8. Process constants

C1	reactor reactivity coeff. [s^{-1}]
M1	reactor mass [Kg]
V1	reactor volume [m^3]
M2	steam generator tube side mass [[Kg]
V2	steam generator tube side volume [m^3]
R1	reactor friction coeff. [bar.s/Kg]
R2	steam generator tube side friction coeff. [bar.s/Kg]
V3	steam generator shell side volume [m^3]
V5	condenser volume [m^3]
V7	pressurizer volume [m^3]
R7	pressurizer heater electric resistance [ohm]
V8	volume control tank volume [m^3]
C10	steam generator safety valve constant [Kg/sec.bar]
C15	pressurizer safety valve constant [Kg/sec.bar]
CT6	turbine constant [Kg/sec.bar]
K23	steam generator heat transmission factor [Mw/deg]
K45	condenser heat transmission factor [Mw/deg]
QQ30	steam generator level control prop. constant [rpm]
TI30	steam generator level control reset time [sec]
QQ31	steam generator pressure control prop. constant[Mw/bar]
TI31	steam generator pressure controller reset time [sec]
QQ32	turbine power control prop. constant [v^{-1}]
TI32	turbine power control reset time [sec]
QQ33	pressurizer level control prop. constant [01]
TI32	pressurizer level control reset time [sec]
C33	pressurizer level controller, pump/valve factor [rpm]
QQ34	pressurizer pressure control prop. constant [bar^{-1}]
TI34	pressurizer pressure control prop. constant reset time [sec]
C34	pressurizer pressure controller, heat/spray factor [V]
C20	reactor cool pump constant [bar/rpm]
R20	reactor cool pump freactor [bar.sec/Kg]
C21	feedwater pump constant [bar/rpm]
R21	feedwater pump freactor coeff [bar.sec/Kg]
C22	cooling water pump constant [bar/rpm]
R22	cooling water pump friction coeff. [bar.sec/Kg]
DP22	cooling water pump pressure head [bar]
C23	volume control pump constant [bar/rpm]
R23	volume control pump friction coeff. [bar.sec/Kg]
GMI6	turbine/generator moment of inertia [Kg.m^2]
CG6	turbine/generator constant [$(v/rpm)^2$]
OMAX6	turbine/generator maximal speed [rpm]
H1	reactor height [m]
H2	steam generator height [m]
CLK2	steam generator tube side leakage coeff. [Kg/s/bar]
QQ35	reactor control rod pos controller prop. constant [m/s]
C35	reactor control rod position feedback coeff. [m^{-1}]

WMAX1	reactor control rod maximal speed [s^{-1}]
OMAX20	reactor cool pump maximal angular velocity [rpm]
OMAX21	feedwater pump maximal angular velocity [rpm]
OMAX22	cooling water pump maximal angular velocity [rpm]
OMAX23	volume control pump maximal angular velocity [rpm]
EMAX7	pressurizer heater maximal voltage [V]
WEMAX6	turbine/generator maximal load [Mw]
OMAX24	reactor cool system oil pump maximal velocity [rpm]
OMAX25	feedwater system oil pump maximal velocity [rpm]
C24	reactor cool system oil pump constant [bar/rpm]
C25	feedwater system oil pump constant [bar/rpm]
R17	reactor cool system oil filter constant [bar.sec/Kg]
R18	feedwater system oil filter constant [bar.sec/Kg]
R19	cooling water filter constant [bar.sec/Kg]

F Model steady state input data

A data input file containing steady state process variable data testing the model in equilibrium is listed below. It contains labelled blocks of initial values for all process variables used for est of the model.

The labels have the following interpretation:

IDENT	Data identification.
DT	Initial value for internal adaptive integration step length.
TMAX	Maximal process time and communication interval (table step length).
ERROR	Limits for relative integration error and limits for adaptive DT.
IC	Initial values for process state variables.
PARAM	Process parameter values.
CONST	Process constant values.
VAR	Initial values for process variables.

Data file content.

```
IDENT
GNP - V1.0, MARTS 1991

DT
  0.125

TMAX
  60.0  1.0

ERROR
  0.005 0.0045  1.0 0.125

IC
  8.560000E+2 3.503581E+4 2.581811E+4 3.061438E+4 2.354863E+4  1.772550E-4
  1.698916E+5 3.490773E+4 2.018634E+4 5.650000E+3 4.000000E+2  8.560000E+2
  8.000000E 1 0.000000E-1 0.000000E-1 0.000000E-1 0.0000000E-1 3.232750E+3
  5.000000E-1

PARAM
  80.0      174.0      0.50       0.50      65.00      30.00
  0.60      158.0     -1.00      -1.00      -1.00      -1.00
 -1.00      -1.00     -1.00      -1.00      -1.00      -1.00
 -1.00      -1.00     -1.00      -1.00      -1.00      -1.00
 -1.00      -1.00     -1.00      -1.00      -1.00      -1.00
 -1.00      -1.00     -1.00      -1.00      -1.00      -1.00
 -1.00      -1.00     -1.00      -1.00      -1.00      -1.00
 -1.00      -1.00     -1.00      -1.00
```

```
CONST
 1.800000E-1 2.308003E+4 3.500000E+1 1.986508E+4 2.720000E+1 8.417356E-4
 6.376785E-4 6.0000E+1   4.260000E+2 5.100000E+1 5.0000E+1   1.130000E+1
 2.153846    1.005063    6.158181    1.236466E+2 1.090749E+2 5.260000E+2
 1.210000E+2 9.650000    7.250000E+1 1.200000E-4 4.500000E-2 4.550000E+1
 1.730000E+2 1.180000E+3 7.400000E-2 1.560000E+2 1.070000E+2 1.945151E-2
 1.479414E-3 3.248400E-1 2.030070E-1 1.666667E-3 1.964650E-5 1.0000
 3.437778E-1 2.812727E+1 1.810000E+5 2.519526E-2 3.0000E+3   2.0000
 5.0000      0.0000      6.200000E-3 9.340000    1.0000E-2   6.0000E+2
 6.0000E+2   6.0000E+2   1.800000E+3 9.500000E+3 5.0000E+2   1.800000E+3
 1.800000E+3 1.111111E-4 1.111111E-4 2.0000E+1   2.0000E+1   1.964650E-5

VAR
 1.613000E+2 1.555000E+2 6.500000E+1 3.200000E-2 1.580000E+2 1.100000
 5.200000E+1 1.300000E+1 3.300000E+2 2.930000E+2 2.791541E+2 2.0000E+1
 2.488441E+1 3.451295E+2 1.500000E+1 1.500000E+1 1.518014    1.299673
 2.779013    1.227360    1.042505E-1 1.768998    1.629765    1.206427
 3.920471E+3 3.920471E+3 3.200284E+2 2.544983E+4 3.200284E+2 3.200284E+2
 8.785418E-2 5.500000    2.544983E+4 0.0         0.0         8.785418E-2
 5.500000    0.0         3.920471E+3 0.0         0.0         8.0000E-1
 0.0         1.520000E-3 5.0000E-1   0.0         0.0         0.0
 0.0         0.0         1.204159    2.900000E-2 8.560000E+2 -5.327663E+2
 5.0000E-1   4.0000E-1   6.0000E-1   5.0000E-1   3.077196E+1 4.925938
 1.751479E+1 6.962025E-2 6.0000E+2   4.0000E+2   6.0000E+2   9.0000E+2
 1.890000E+2 2.784363    3.0000E+1   3.232337E+2 3.232337E+2 8.560000E+2
 1.800000E+3 1.0000E-2   6.045454E+1 1.800000E+3 1.0000E-2   6.045454E+1
```

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Abstract (Max. 2000 characters)

A computer model of a simplified pressurized nuclear power plant is developed with aim at studies concerning process control, diagnosis and decision making.

The model includes the traditional PWR plant components, primary circuit with reactor, pressurizer and steam generator, steam circuit with steam line, turbine and condenser, interconnected with pumps, valves and controllers. The model can be used for calculation of transients for both normal operation and incidents such as turbine trip, loss of feedwater, run down of pumps or various valve failures.

The computer model is not directed to any specific existing plant. For convenience and alleviation in implementation the physical description of many components are simplified to an extent where the qualitative behavior of the system is not violated. For computer memory economy a variety of thermodynamical functions for water and steam have been approximated with analytical expressions based on table values.

The model is implemented in the C language and has been run on both the IBM PC and the SUN workstation.

Descriptors INIS/EDB

COMPUTERIZED SIMULATION; MATHEMATICAL MODELS; PWR TYPE REACTORS; REACTOR CONTROL SYSTEMS; REACTOR OPERATION

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